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Heavy ion fusion energy program in Russia

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Abstract

An overview of the activities in progress of the Russian Heavy-Ion Fusion Energy community is given for the period since the last Symposium in Heidelberg in 1997. The progress in up-grading of the ITEP accelerator complex (project ITEP-TWAC), target simulations and recent results on heavy ion beam–plasma interaction physics are emphasized.

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1. Introduction

There are numerous important changes in the development of Heavy-Ion Fusion energy (HIFE) program in Russia in the last two years. Scientific Council of Minatom of Russian Federation has approved the activities on HIFE and gave the green signal to the funding of the ITEP-TWAC project for period 1999–2002. Structural stability for collaboration of the main participants ITEP-Moscow and VNIIEF-Sarov are given by two big projects:

- Up-grading of ITEP accelerator complex (project ITEP-TWAC), funded by Minatom RF, and
- Project # 1137 funded by ISTC.

Scientific groups and individuals from about 10 institutions are involved in activities on HIFE. Overall funding of activities was doubled in 1999 compared to 1998 and was increased by a factor ~1.5 in 2000. The list of key issues of the Russian HIFE program includes:

- numerical simulations related to the HIFE target design,
- heavy ion accelerator physics,
- theoretical and experimental investigations of the state of matter under extreme conditions,
- experimental and theoretical study on beam–plasma interaction.

2. TeraWatt accumulator project

A significant part of the activities of Russian HIFE community concentrates on the TeraWatt Accumulator project (ITEP-TWAC) in progress in ITEP-Moscow now. The goal of the project is to take advantage of existing accelerator facility based on two heavy ion synchrotron rings for

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high current HIFE related experiments. Non-Liouvillian stripping technique [1] is applied for stacking of many pulses accelerated in synchrotron UK into the storage ring U-10, see Fig. 1. Full stripping of He-like medium atomic mass ions is used to provide high efficiency of the non-Liouvillian stacking process. The whole acceleration-accumulation scenario looks as follows. A laser ion source produces about 5×10^{10} ions, which are accelerated in the pre-injector U-3 up to 1.6 MV/u, then injected into the 13 Tm booster ring UK (see Fig. 1). After acceleration up to 0.7 GeV/u, a 250 ns long bunch is injected in a single turn mode to the synchrotron ring U-10 using a non-Liovillian stripping process. The charge state of the ions changes from He-like (two electrons of the inner atomic K-shell remain) to fully stripped by passing through a solid foil of about 5 mg/cm^2. The stripped beam is accepted by the synchrotron U-10, which serves as a storage ring, while no further acceleration is provided. To minimize the effect of the stripping foil, the accumulated beam circulating in the storage ring is directed on the stripper target only during the injection cycle of the next ion beam pulse coming from the UK booster. For this purpose a kicker-system for the beam, based on two fast coherent deflectors is foreseen. Since the cross-section of the accumulated beam is at least 25 times larger than the surface-area of the stripper target, the beam quality is expected not to deteriorate significantly by the scattering in the foil. Repeating this process several hundred times provides accumulation in the coasting beam until the Laslett space-charge limit (≈ 0.16) is reached in the synchrotron ring. A rapid switch on the RF in the synchrotron ring causes ballistic compression of the accumulated bunch from a length of 1000 ns down to ~ 100 ns.

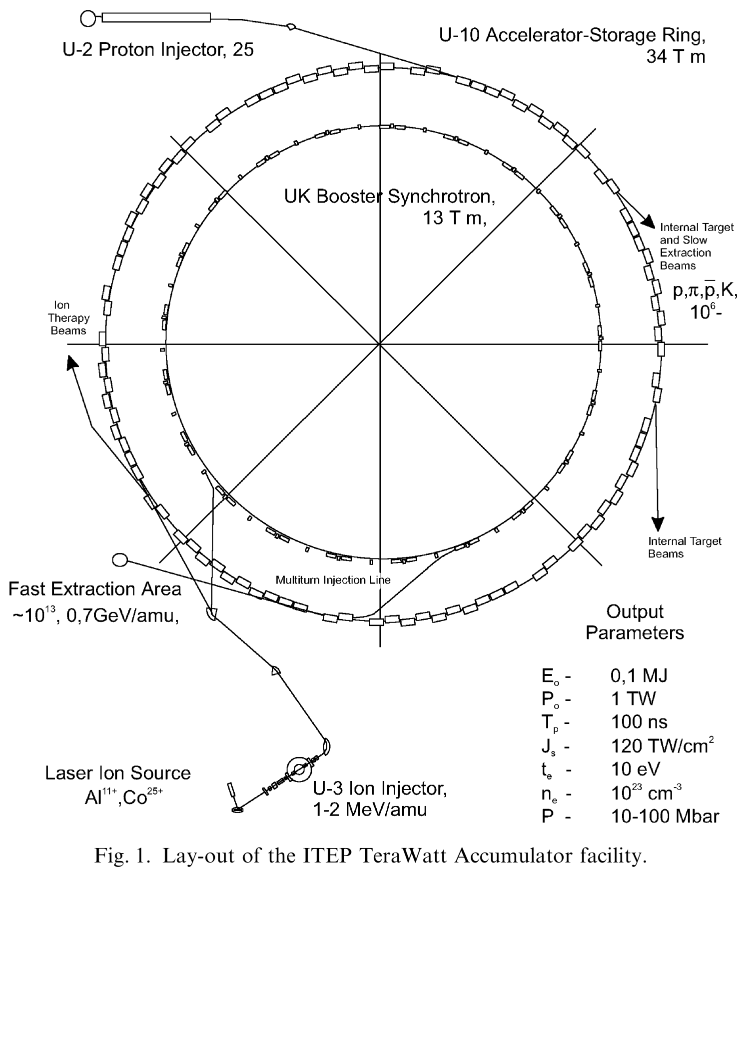

Fig. 1. Lay-out of the ITEP TeraWatt Accumulator facility.

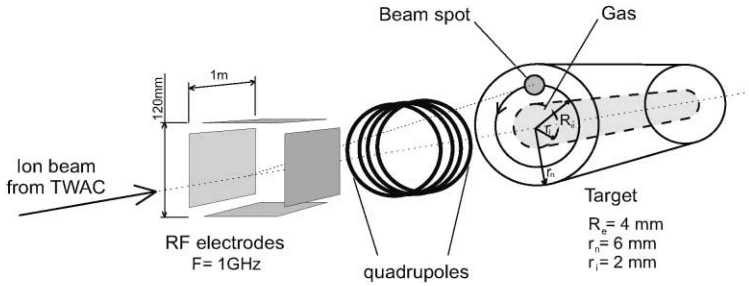

Fig. 2. Scheme of the RF rotational target illumination system.

After compression, the bunch is extracted, transported and focused onto the target. The beam emittance of 5 cm mrad enables focusing down to a spot-size of ~ 1 mm in diameter.

The status of construction and commissioning of key elements of the accelerator facility at the beginning of March 2000 looks as follows:

1. Laser ion source, based on 5 J/0.5 Hz TEA CO_2-laser, has been set in operation and installed in U3 pre-injector area. The 20 mA/20 μs Carbon ion beam was matched to the 2 MV/2.5 MHz U3preinjector.
2. The accelerated beam of 16 MeV C^{4+} ions is guided by the beam transport line up to UK ring and injected. Intensity measured at injection point is $\sim 1.5 \times 10^{10}$/15 μs. Circulation of the C^{4+} beam in UK ring at constant B field is obtained.
3. Magnetic components of the beam-transfer line connecting UK and U-10 rings, as well as of the multi-turn injection system have been manufactured and are in the process of installation and adjustment.
4. Powerful CO_2-laser with output parameters ~ 100 J/20 ns and rep-rate of ~ 1 Hz is under construction now.
5. Beam transport line for the extracted beam to the beam-target interaction area is under design.
6. Up-grading of RF, vacuum and power supplies systems of both the synchrotron rings are in progress.
7. Pre-commissioning of the TWAC accelerator facility with demonstration of multi-turn stacking procedure for C^{6+} ions is scheduled for December 2000.

The expected output parameters of the ITEP-TWAC facility [1] give strong motivation for numerical simulations of forthcoming experiments on intense heavy ion beam–plasma interaction related to the physics of HIF targets. The most promising appears to be the cylindrical geometry of the energy deposition region, inherent for TWAC beams. A multi-D, three temperature hydrodynamic Eulerian code has been developed for this purpose in ITEP [2]. It includes radiation transport and electron heat conductivity in diffusion approximation. Nuclear reactions and diffusion of charged particles are taken into account. This code is suitable for simulations of cylindrical conversion of multi-layers directly driven HIF targets with magnetized fuel. Capabilities of the code enable to follow the *R–T* instability and mixing of the layers.

A hollow beam combined with a hollow cylindrical target can provide extremely high densities and pressures on the axis of converging cylinder [3]. For performance of this kind of experiments a special RF system providing fast rotation of the TWAC beam is suggested in Fig. 2. Such a system can produce homogeneous irradiation of directly driven cylindrical layer.

3. Accelerator physics issues

In the theoretical studies of accelerator physics emphasis is laid on the optimization of accumulation process in storage rings by using charge exchange injection and the electron cooling. Gaussian beam method and Monte-Carlo code have been employed for the beam evolution analysis in course of accumulation process.

The Intra-Beam Scattering (IBS) has been found to be the main source for limitation of the phase space density of the accumulated beam. The IBS, leading to the energy transfer from the transverse plane to the longitudinal one, accompanied by random interaction of the beam with the stripping foil can result in considerable ion losses and in increase of the final momentum spread. Both mechanisms prevent the high final compression rate of the beam.

Two ways to suppress the influence of these negative processes are suggested. One is to reduce the injection time by increasing the intensity and the rep-rate of the injected beam. The other is the implementation of the electron cooling which can give significant enhancement of the beam specific power and therefore of the plasma temperature of the irradiated target. Optimization of the accumulation scenario for $^{27}Al^{+13}$ shows the plasma temperature reaches saturation after ca.150 injection cycles for slow injection ($\sim 10^{10}$ ions per injection cycle) and 10–15 cycles for fast injection ($\sim 10^{11}$ ions).

Analysis of the coherent effects [4] has shown, that the most important is the transverse instability, induced due to the beam interaction with environment and with electrons, appearing by ionization of residual gas. For ion beam with small momentum spread required for beam compression, special broadband damping system suppressing the dipole instabilities is necessary.

4. Heavy ion beam–plasma interaction physics

Studies of the beam–plasma interaction physics have been continued within the framework of wide international collaboration. Motivation for these activities is given by the necessity of precise matching of the geometric parameters of the low Z converter of an HIF target to the beam energy deposition profile. The effects governing the physical stopping length in matter have been studied in numerical simulations and in related experiments. Numerical simulations for nuclear fragmentation of different ion species in wide range of ion energies (from 100 MeV/u to 1 GeV/u) were carried out. The results show this effect can be neglected for ion energy less than 100 MeV/n. But for higher energies, up to several percent of the total beam energy can be deposited outside the fiducial converter layer.

Influence of the energy straggling induced by finite $\Delta p/p$: of the 50 MeV/n ion beam in Be target as well as of the stochastic straggling of Coulomb collisions was investigated numerically by means of SRIM [5] and SIDEST codes [6].

In order to verify the results of numerical simulations a number of experiments have been performed by using the existing low intensity accelerators in combination with plasma targets. For this purpose carbon, krypton and lead ion beams from UNILAC in GSI are used for systematic study of charge dependent stopping of ions in capillary plasma target [7]. Explosively driven plasma target [8] has been tested with 3 MeV proton beam at ITEP experimental area with respect to the forthcoming experiments on ion stopping in non-ideal plasma.

5. Conclusions

Russian HIFE program comprises theoretical and experimental activities on HIF targets design, study of accelerator-driver issues, beam–plasma interaction and basics of high energy density in matter generated by intense heavy ion beams.

- The essential part of the activity of Russian HIFE community is the TWAC project in progress in ITEP-Moscow now. Pre-commissioning of the key elements of the accelerator facility and demonstration of the beam gymnastics is scheduled for the end of 2000.
- Significant results have been obtained in numerical simulations of the state of matter under extreme conditions generated by heavy ion beams with parameters corresponding to those expected from the ITEP-TWAC facility. Detectable level of the neutron yield is predicted in course of cylindrical compression.

- Important step forward has been achieved in numerical investigations of the beam dynamics, in particular, for ITEP-TWAC accumulator ring.
- New experimental results on ion stopping in capillary plasma target and in explosively driven shock compressed plasma have been obtained.

Acknowledgements

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